

The Annealing of Copper: With Special Reference to Dilatation

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SECTION A.—MATHEMATICAL AND PHYSICAL SCIENCES.

The Annealing of Copper : with Special Reference to Dilatation.

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(Communicated by Professor J. H. Poynting, F.R.S. Received May 21,—Read June 27, 1907.)

It is well known that copper is met with in two distinct forms, viz., the soft state as in cast or annealed metal, and the hard variety which is the result of mechanical work. There is more difference between the mechanical properties of hard and of soft copper than is observed in the case of two distinct metals; such, for example, as nickel and cobalt.

For instance, one of the most important of these differences, from a practical point of view, is in connection with the tensile strength of the material, which is only about 10 to 14 tons per square inch in cast or in annealed copper, while in hardened copper the tenacity is about twice as great, and usually runs from about 20 to 28 tons per square inch, or even more in special cases. The difference between hard and soft copper can be also readily illustrated by bending two rods about $\frac{1}{4}$ inch square section, one in the hardened and the other in the annealed condition. The latter can be easily bent in the hands or even tied in a knot, while the mechanically worked bar is rigid and elastic, and can only be bent by the application of considerable force. It is common knowledge that hard copper becomes perfectly annealed by heating to 500° C.; that the heating need not be for any lengthened period, and the rate of cooling afterwards is unimportant.

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Changes of properties which are so marked, and so far-reaching in the applications of metallic copper, have naturally been the subject of investigation by metallurgists and physicists, among whom may be specially mentioned Roberts-Austen,* Rudeloff,† Thurston,‡ and Heyn.§ These researches deal chiefly with the mechanical properties of copper in various conditions, and at various temperatures.

In addition to the foregoing, reference should be made to the work of Beilby,|| who has investigated the microstructure of copper in different states; while the expansion of copper, over a considerable range of temperature, was observed by Dittenberger and Gehrke.¶ No particulars are given in their report as to the condition of the metal under examination; but its expansion up to a temperature of 625° C. is stated to be in agreement with the formula

$$\lambda = 10^{-9}(16070 + 4.030 t^2),$$

while a rod 487 mm. long showed a permanent extension of 0.01 to 0.02 mm. on resuming the original temperature.

In the course of an investigation recently conducted at the University of Birmingham on the volume changes during the solidification of cast metals, it was shown that corresponding with each temperature arrest during the cooling of cast iron there was also a definite volume alteration.** It was also shown that copper zinc alloys expand during solidification. For these experiments a simple form of extensometer was employed, and the indications of this instrument show that at certain temperatures, which marked well defined changes in the properties of the solid metal, there were well marked alterations of volume, which were rendered very evident by the extensometer.

It was thought that by the application of somewhat similar methods, information might be obtained as to any abrupt or definite change which may occur when metal, which has been subjected to mechanical work, is, by annealing, converted into the soft variety.

* Roberts-Austen, W., 2nd Report Alloys Research Committee, 'Proc. Inst. Mech. Eng.,' April, 1893, p. 114.

† Rudeloff, M., "Influence of Temperature on Tensile Strength of Metals," 'Mittheil. König. Technische Versuchs-Anstalt,' 1894, vol. 11 (b), pp. 292—330; "Influence of Heat, Chemical Composition and Mechanical Treatment on Strength and Ductility of Copper," 'Mittheil. König. Technische Versuchs-Anstalt,' 1898, vol. 16 (a), pp. 171—219.

‡ Thurston, 'Materials of Engineering,' Part III, pp. 477—573.

§ Heyn, E., "Overheating of Mild Steel" (refers to copper), 'Journ. Iron and Steel Inst.,' 1902, vol. 2, p. 101.

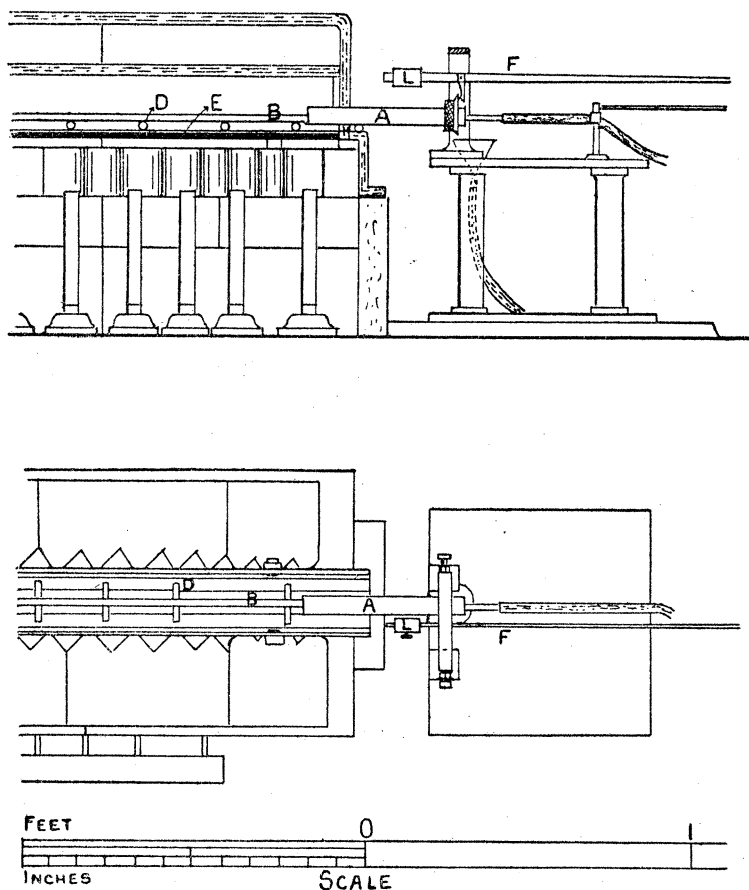
|| Beilby, G., 'Journ. Soc. Chem. Ind.,' 1903, pp. 1107—8; 1904, p. 788.

¶ Report of Physikalisch-Technische Reichsanstalt, by Holborn and Grüneisen, 1902, abstracted in 'Engineering,' vol. 4, No. 24.

** T. Turner, "Volume and Temperature Changes during the Cooling of Cast Iron," 'Journal of the Iron and Steel Institute,' 1906, vol. 1, p. 48.

In order to make the desired observations an extensometer was devised capable of indicating the changes of length of a bar of copper at temperatures from that of the atmosphere to about 700° C. At the same time the temperature of the bar was ascertained by a pyrometer of the Le Chatelier thermo-junction type.

The general arrangement of the apparatus is shown in fig. 1; whilst fig. 2 represents, on a larger scale, details of the method of connecting with the extensometer.



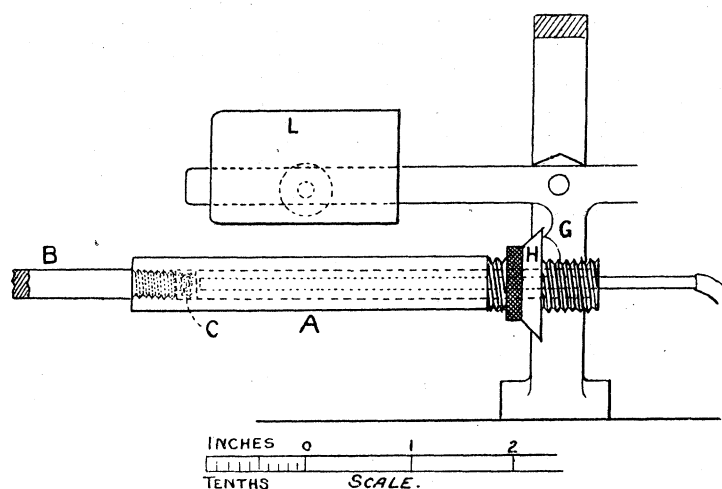
ARRANGEMENT OF APPARATUS FOR MEASURING DILATATION.

FIG. 1.

Numerous forms of apparatus were tried before the final design was adopted, as it was essential to heat the bar uniformly and to ensure that the expansion of the whole length and of that alone should be recorded, the difficulty being

to connect the bar, which was of considerable length and entirely in the furnace, with the extensometer, which was situated at some little distance away.

The bars used in the series of experiments were all $\frac{1}{4}$ inch in square section and 35 inches long. Each bar (B) was heated in a gas fired tube furnace as subsequently described; and, in order to confine the rise of temperature to the bars, they were fitted at each end with a copper tube (A) 4 inches in length. This tube was screwed on to the bar for a distance of about $\frac{1}{2}$ inch, and projected about 3 inches beyond the end of the furnace. The bar itself was thus entirely in the furnace, and in order to prevent the expansion of the connecting tubes being recorded they were water cooled, while the end of



DETAILS OF EXTENSOMETER CONNECTION.

FIG. 2.

the bar inside the tube was covered with an asbestos plug (c) so as to prevent the water having any cooling effect in it. One of these copper tubes was firmly clamped so as to be kept quite rigid, while to the tube at the other end the extensometer was attached. In this way the expansion of the whole length of the bar was obtained, while the rest of the system was maintained at a constant temperature.

In order to allow freedom of motion in the direction of its length, the rod rested on a number of small porcelain rollers (D) which were supported on a trough made of steel bars, $\frac{1}{4}$ inch thick and 3 inches wide. The trough is open at both ends, and in order to prevent buckling effects due to the heat it was well braced, whilst the rollers, instead of running directly on the bottom

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of the trough, were supported by two thin strips of steel. In the earlier experiments with a thinner trough, there was sufficient buckling to seriously affect the observations.

The trough was heated by a series of bunsen burners, controlled by a common tap, and so placed as to ensure, as nearly as possible, uniformity of heating. It is known that tube furnaces are usually cooler at the ends than in the middle, and pyrometric tests were made throughout the trough in order to determine the proper number and spacing of the gas burners. By surrounding the trough with brickwork, covering the ends and top with asbestos cardboard, and providing a considerable covered air space around the trough, it was ultimately found possible to ensure very considerable uniformity of temperature throughout the tube.

The extensometer consisted essentially of a bell crank lever (F) mounted on pivots; the indicating arm was 25 inches long, whilst the short arm was so fashioned that at a distance of $\frac{1}{2}$ inch from the pivots it took the form of a finely rounded projection (G). This pressed against a brightly polished disc (H) screwed on to one of the connecting tubes, by means of which the forward motion of the disc (*i.e.*, the expansion of the rod) was indicated on a scale (K), which was an arc of a circle divided in millimetres.

The extensometer worked in a vertical plane, and was very delicately mounted so as to reduce the effects of friction to a minimum. On being tested by a micrometer screw its indications were found to be fairly uniform in all positions, and the millimetre scale denoted a magnification of 48; in other words, 1 mm. scale-division corresponded to an expansion of $1/1200$ of an inch. The indicating arm was extended backwards for some distance beyond the pivots, so as to accommodate a balance weight (L), which was, however, placed at such a distance as to always insure a small positive pressure against the brass disc in whatever position the indicator arm might happen to be situated. As the copper connecting tube at the other end was firmly clamped, it was only necessary to take the extensometer readings from one end in order to measure the expansion.

The extensometer was made in the Metallurgical Department of the University of Birmingham, by Mr. J. Ward, the University steel melter, and the authors desire here to acknowledge the value of the assistance thus rendered by Mr. Ward.

The temperatures were recorded by a thermocouple, the junction (M) being placed in an $\frac{1}{8}$ -inch hole bored in the centre of the bar under examination. The leads from the cold junction were connected with a dead-beat galvanometer of the D'Arsonval type, in the mirror of which the

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reflections of a graduated scale were observed through a telescope placed some distance away.

The adjustments of the apparatus required careful attention, and the precautions detailed in the foregoing paragraphs were adopted as the result of a very large number of experiments at the commencement of the work. These tests showed that minute frictional effects, slight draughts, and other very small deviations led to irregularity in the results obtained.

The quantity of asbestos used as a non-conducting plug at the end of the rod, the use of steel strips for the rollers to run upon, the adoption of movable bunsens instead of the usual form of combustion furnace, and the careful adjustment of the counter-balance on the extensometer were all decided on after a number of early failures. More uniform results were obtained when the junction was inserted in a hole in the metal instead of fastening it on the surface, whilst the exclusion of draughts by employing brickwork and asbestos protection was most important. Marked effects were also produced by any irregularity in the supply of cooling water to the ends of the rod, and it was considered advisable to run the water under a constant head from a fixed reservoir some feet above the level of the apparatus. The actual operations were conducted as follows.

The adjustments of the apparatus being made so that the indicator was near, but not at the bottom of the scale, the clamps were made tight, and a gentle stream of water was set flowing through the connecting tubes for some minutes, zero readings were noted, the bunsens were then lighted at the full, and observations taken of the indicator and the galvanometer at intervals of 15 seconds.

The changes, which were at first rapid, become gradually smaller, and after a red heat had been attained, half-minute, then one-minute, and finally two-minute intervals were allowed between the readings until the maximum temperature had been reached, at which point the readings had become practically constant. The gas was then turned off, and readings were taken during the cooling of the bar. The results were then plotted so as to give a continuous record of the changes of length and of the increments of temperature.

Preliminary Experiments.

The first series of experiments was undertaken in order to test the delicacy of the apparatus and the trustworthiness of the method. The object was to ascertain whether, when a material was employed which is known to undergo abrupt changes of length at certain critical points, these changes could be readily and accurately observed, and, secondly, to determine

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whether, in the case of a material which undergoes no such abrupt changes, a perfectly continuous curve could be obtained.

The materials which suggested themselves as being most suitable for the above purposes were steel and wrought iron, as it is well known that with high carbon steel there is an abrupt change of volume at about 680° C., while no such change takes place with wrought iron. The change in volume in the case of steel is known to be connected with the state of combination of the carbon which is present, and this volume change is accompanied by marked differences in hardness and other properties.

The wrought-iron bars used for these tests were of best Staffordshire iron, and contained 0.03 per cent. of carbon. The steel was made in the Siemens furnace, and contained 0.94 per cent. of carbon. The bars were, as before described, 35 inches long, $\frac{1}{4}$ inch square section, and the experiments were all conducted exactly as previously mentioned.

(a) *Wrought Iron*.—The curves obtained from heating and cooling a bar of wrought iron are shown on fig. 3. From these it will be seen that within the range of temperature employed the curves are regular and continuous, and the absence of any break or arrest may be taken to indicate that the apparatus was satisfactory, and that the precautions previously mentioned had eliminated all important sources of error.

(b) *Steel*.—The curves obtained from the steel with 0.94 per cent. of carbon are also given in fig. 3, and these indicate that a marked diminution in length occurs at the temperature arrest point, A_{r1} , which corresponds with about 680° C. On cooling the bar a corresponding increase of length occurs at the same temperature.

M. H. le Chatelier* has already, by an entirely different method, determined the expansions of iron and steel at various temperatures, and the results of the present experiments given above are in practical agreement with his observations. Messrs. Charpy and Grenet† have also studied the transformations of steel by the dilatometric method, using the method of Le Chatelier. These observers point out that in order to obtain satisfactory numerical values it is necessary to heat at a sufficiently slow speed, and state that about 200° per hour is a suitable increment, a rate which does not differ very markedly from that adopted in the present series of experiments. Charpy and Grenet also found that in all steels, and cast iron containing only carbon, the transformation took place at about 700° C.; that with low carbon steels the contraction at this temperature was inappreciable; and that the

* 'L'Etude des Alliages,' Paris, 1901, p. 403.

† 'The Metallographist,' 1903, p. 240; 'Comptes Rendus Académie des Sciences,' May 10, 1902.

maximum contraction was observed in steels which contained 0·93 per cent. of carbon.

As the curves obtained both for iron and steel by the extensometer apparatus agreed with those of previous experimenters, alike in the character and extent of the changes which take place, and the temperature at which any irregularity is noted, it may be assumed that the accuracy and suitability of the method of investigation was sufficiently proved. It was therefore possible, with confidence, to approach the real object of the research.

Dilatation of Hard-drawn Copper.

The rods used in these tests correspond in every way with those employed in the tests for iron and steel, being 35 inches long, a $\frac{1}{4}$ inch in square section, and screwed to water-cooled copper connecting-tubes as before. The rods were supplied by Messrs. Thos. Bolton and Sons, of Oakamoor, Staffs, and were of electrolytic copper of selected quality and uniformity. They had been rolled while hot down to $\frac{3}{8}$ inch square, and were afterwards cold drawn until $\frac{1}{4}$ inch square. The curve obtained on heating a bar of this hard-drawn copper to about 580° C. is given in fig. 4. At this temperature the metal is completely annealed, and, on cooling, is dead soft. It will be observed that both the heating and cooling curves are quite regular, there being no break such as would be caused by the slightest abrupt change of volume at a critical temperature. There was nothing observed which would serve to indicate at exactly what temperature hard copper passes into the soft variety. As a check upon the results obtained by the extensometer, the rod was marked before being placed in the furnace, a length of 30 inches being taken, and when the metal was cold, after the conclusion of the experiment, there was no perceptible alteration of length in the marked portion.

Dilatation of Annealed Copper.

The annealed rod, as used in the previous experiments, was now heated to about 600° C., and afterwards allowed to cool slowly to the temperature of the atmosphere. From the curves obtained (fig. 4) it will be observed that the dilatation was as regular as with wrought iron, and quite similar to what was observed with the hard-drawn copper. It thus appears that the change from the hard elastic condition of worked copper to that of extremely soft metal, such as is obtained with fully annealed copper, is not accompanied by any alteration of length. It may be recalled that it is usual to make allowances in practice for the volume changes which accompany the cooling of cast iron or the hardening of steel; while we are informed, by Mr. F. Platten, of

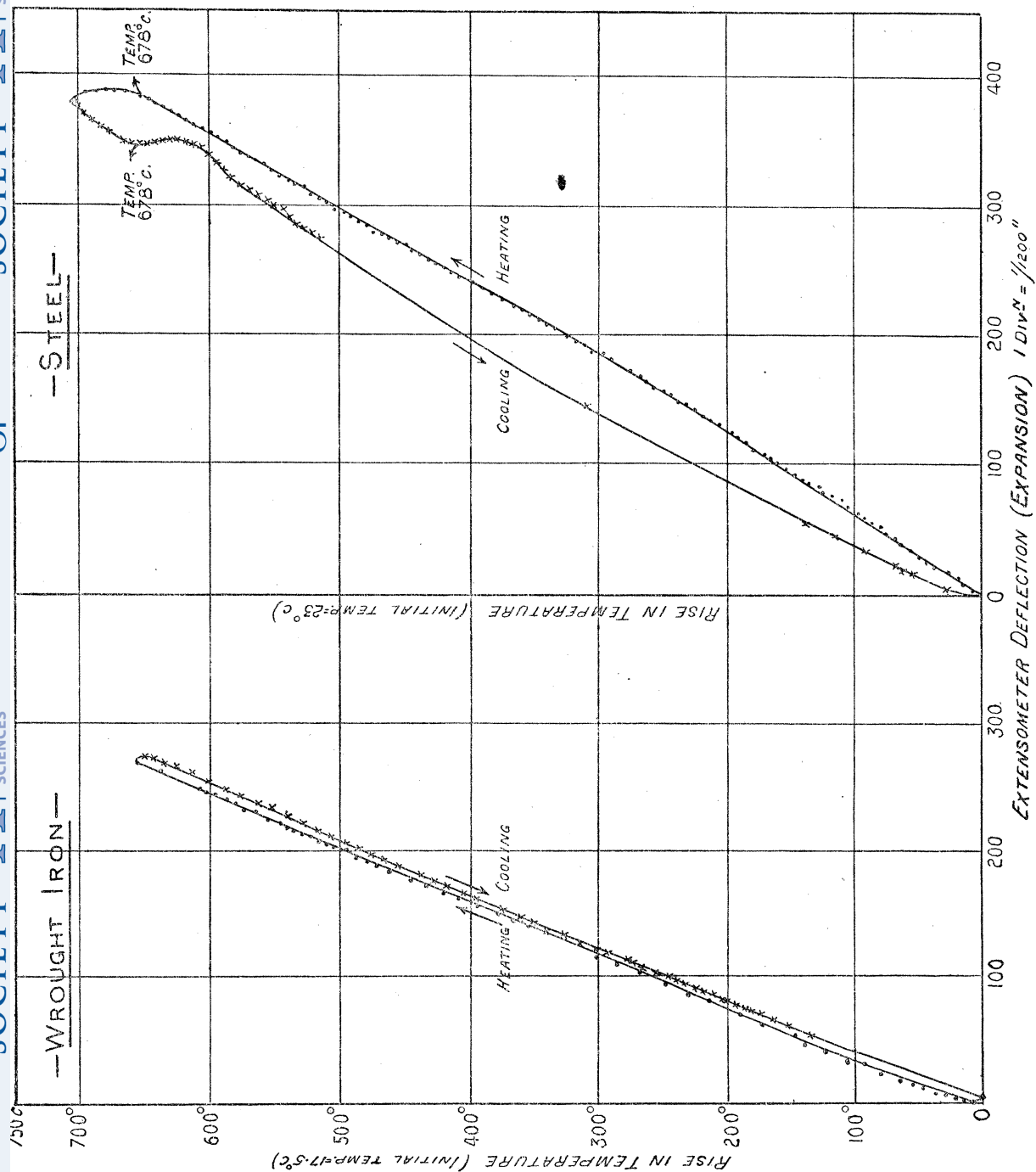


FIG. 3.

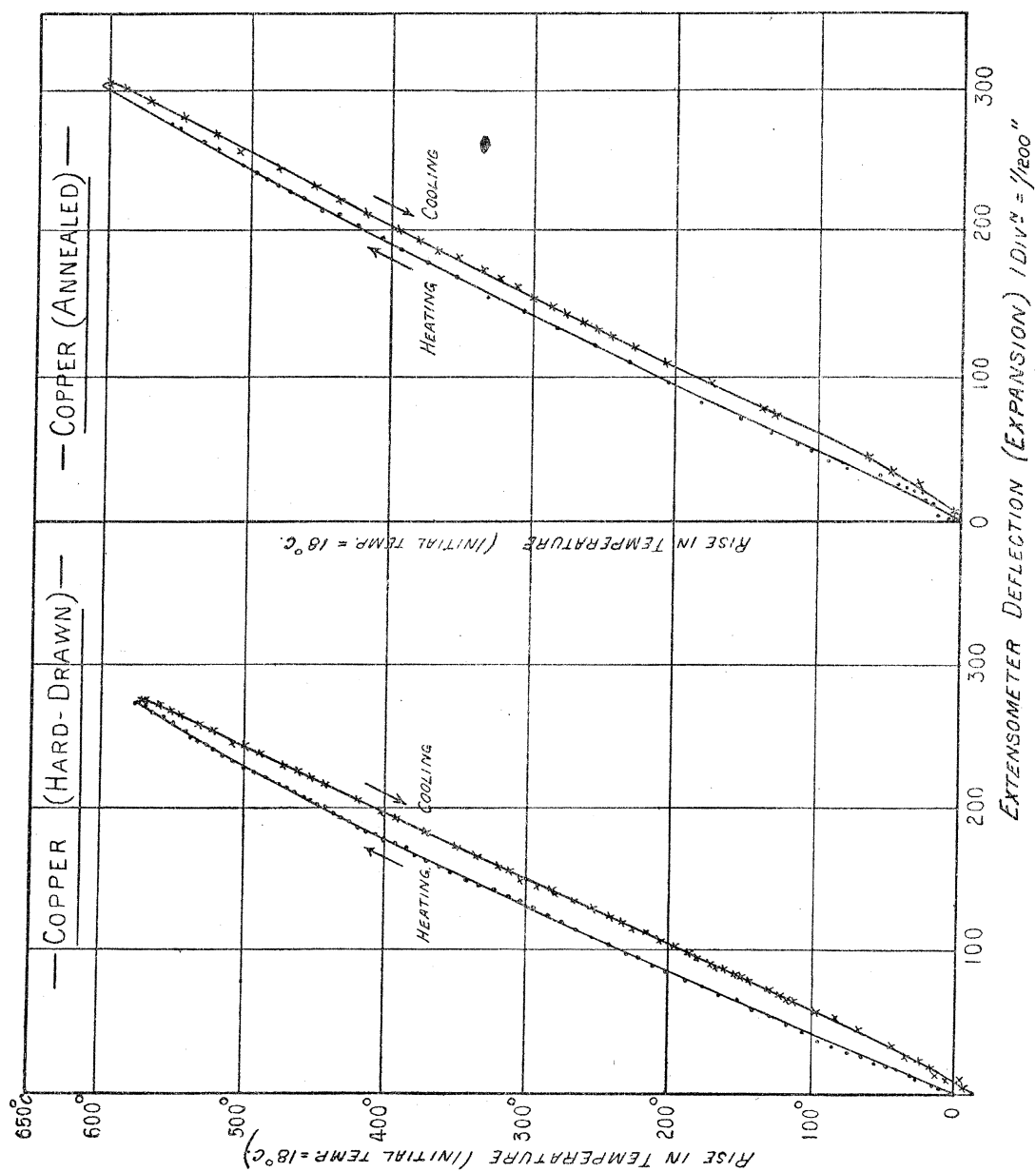


FIG. 4.

Elliott's Metal Company, Limited, that, on the other hand, no allowance is made, when annealing hard copper in the processes of rolling or drawing, for any alterations in length or thickness.

Dilatation of Copper Alloys.

It was now considered advisable to examine certain well-known copper alloys which are of commercial importance; which are hardened by work, and which may be annealed at a relatively low temperature like copper itself. For this purpose Mr. Platten kindly supplied hard-drawn $\frac{1}{4}$ -inch-square rods having the following composition:—

- | | |
|-------------------------------|---------------------|
| 1. Brass (copper 70, zinc 30) | 4. Gun metal. |
| 2. „ („ 66, „ 34) | 5. Phosphor bronze. |
| 3. „ („ 60, „ 40) | |

These were examined in 35-inch lengths exactly as in the previous experiments, and the results plotted. No satisfactory curve was obtained of the 60:40 brass as all the rods of this composition which were tested behaved in a curious manner, showing a normal expansion up to a certain point and then beginning to develop a helical twist which rendered it impossible to obtain any trustworthy indications with the extensometer, as the bars were no longer straight. The other four alloys, namely 70:30 brass; 66:34 brass, gunmetal, and phosphor bronze gave perfectly regular and uniform curves as the temperature rose, and no indication was afforded as to the point at which the hard metal became annealed. The cooling curves were all quite regular, and similar to each other, though the contraction was very slightly more rapid above 400° and slightly less rapid below 400° than might have been expected from the heating curve.

The conclusion to be drawn from these experiments would appear to be that the alterations which take place when hard copper is by annealing converted into the soft variety are unaccompanied by any change in linear dimensions. It is known that the separation of a constituent, as of graphite from cast iron or pearlite from steel, is accompanied by marked dilatometric changes. Le Chatelier* has shown that a dimorphic transformation such as that which ferrous sulphide undergoes between 100° and 150°, is accompanied by a marked change of volume. Allotropic changes in an element are also usually accompanied by marked alterations of volume, as in the case of pure iron at about 880° C. It is evident, therefore, that such changes in the properties of copper and of copper alloys as are caused by mechanical work or

* 'Metallographist,' 1903, p. 23; 'Bulletin de la Société d'Encouragement,' September, 1902.

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annealing respectively are of a different order to those which are due to allotropic or dimorphic transformations, or to the separation or rearrangement of constituents. The results here recorded lead us to believe that mechanical work produces only internal rearrangement of the metallic grains or molecules, but does not lead to any chemical or physical changes such as are correctly regarded as allotropic. We have met with no evidence to support the view that allotropic change results from mechanical work.

A New Current Weigher, and a Determination of the Electromotive Force of the Normal Weston Cadmium Cell.

By Professor W. E. AYRTON, F.R.S., and T. MATHER, F.R.S., Central Technical College, London, and F. E. SMITH, A.R.C.S., National Physical Laboratory, Teddington.

(Received June 5,—Read June 27, 1907.)

(Abstract.)

Introductory.

The instrument described is the outcome of conversations between the late Professor J. Viriamu Jones, F.R.S., and one of the authors (W. E. A.), on their return from the British Association Meeting held in Toronto in 1897. Its object was to determine “the ampere” as defined in the C.G.S. system, to an accuracy comparable with that attained in the absolute determination of the ohm by Lorenz’s apparatus, an account of which was given by Professors Ayrton and Jones at the Toronto Meeting.*

Professor Jones had previously developed a convenient formula for calculating the electromagnetic force between a helical current and a coaxial current sheet, viz.,

$$F = \gamma_A \gamma (M_2 - M_1), \dagger$$

where γ_A is the current in the helix, γ the current per unit length of the current sheet, and M_1 , M_2 the coefficients of mutual induction of the helix and the two ends of the current sheet respectively. By using coaxial coils with single layers of wire wound in screw-thread grooves, advantage could be taken of the above formula.

* See ‘B. A. Report,’ Toronto, 1897, p. 212.

† ‘Roy. Soc. Proc.,’ vol. 63, p. 204.